Model-based thermoeconomic assessment and selection of alternative configurations for crude-oil tankers discharge systems

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Abstract:

This paper presents the thermoeconomic assessment and design of alternative cargo unloading system configurations of crude oil tanker vessels via modelling and simulation techniques. A typical-in-practice Rankine-cycle system was synthesised in our modelling framework DNV GL COSSMOS to describe the thermodynamic behaviour of the baseline system. Then, three alternative configurations were examined: a) the addition of a micro steam turbogenerator to utilise the potential steam rejection that may take place during an operation at low load; b) the addition of superheaters in the boiler to drive the steam turbines; c) the replacement of one steam turbine driven pump by a variable frequency electric driven pump. To assess the system for the actual operation, a realistic operating profile was used based on on-board measurements from discharge operations of an Aframax cargo-oil tanker over one year. The thermoeconomic comparison of the alternative designs is based on operational, capital, and installation costs. The operational costs of each design (fuel and energy consumption) were estimated based on the simulation of system performance. Capital and installation costs were estimated based on economic data from similar previous applications. The alternative designs were assessed both for new built vessels and as potential retrofit solutions for existing vessels. Sensitivity analysis with respect to capital costs and the fuel oil price complete this study.

Keywords:

Marine energy systems, Process modelling, Rankine cycle, Tanker operations, Thermoeconomic assessment.

1. Introduction

Shipping holds a significant role in the world trade since it is responsible for more than 90% of the international trade of goods, representing approximately 11% of the global transport-related oil consumption [1, 2]. Oil-tankers are the only way for over-seas transport of crude-oil and petroleum products, which are among the main energy sources of almost all industries, as 32% of the global energy production is fuelled by oil [3]. Approximately 65% of the annual oil production is transported by oil-tankers [4], while 2.9 billion tons of oil and petroleum products are unloaded annually [1].

Over the last years, stringent emissions regulations, fuel prices volatility, and global economic crisis have shifted the industry to more environmental-friendly system designs and ways to improve the operation to minimise the fuel consumption and emissions. One of the greatest energy consumers on-board tankers is the discharge system, which is responsible for the offloading of the cargo from the cargo tanks to the terminal on-shore. The transport capability of a tanker varies from 50,000 tons, for a panamax tanker, to 350,000, for very large crude-oil carriers (VLCC). The typical discharge operation duration is between one and four days depending on the cargo quantity, terminal conditions and constraints, and the vessel schedule.

The most common in-practice crude-oil discharge system configuration is based on oil-fired boilers in a Rankine cycle, driving steam turbines that ultimately drive the cargo pumps. Such systems demonstrate inherently low efficiency and a large potential for improvement from the operational aspect, as demonstrated in [5]. The current designs are based on existing experience, crew operational knowledge, and the need to cover other service steam demands of the vessel. However, technological developments in some fields, e.g. electric machines and micro steam turbines, provide alternatives that may yield greater system efficiency, consuming less fuel and producing fewer emissions.

In this paper we present the model-based techno-economic assessment and comparison of three alternative cargo discharge systems for oil-tankers. In section 2, the baseline and alternatives systems are described, while section 3 provides the mathematical model formulation and description of our modelling framework DNV GL COSSMOS. Finally, section 4 presents the operating profile that was used for the simulations and the results including the comparison of the different system layouts.

2. Systems description

The two main types of cargo discharge systems are steam-driven and electric-driven ones. The majority of the vessels utilise the former, due to the fact that large steam production is required to cover also other steam demands on-board, and thus utilise large boilers. The latter are utilised usually by ships with electric propulsion that are able to cover all the vessel demands utilising electric power. In this work we focus on steam-driven systems.

The discharge systems are independent of the propulsion system; they comprise of steam turbine-driven pumps and oil-fired marine boilers. Detailed description of those systems can be found in [5]. Typically, in large crude-oil tanker vessels the system consists of two boilers, three steam turbines, three pumps, a vacuum condenser, a feed water tank, and the piping system (Fig. 1). The system's primary function is to pump the cargo to the shore terminal, while it also serves a secondary goal of supplying the vessel's tanks with inert gas, i.e. low-oxygen content exhaust gas from the boilers. It should be noted that the boilers cover any additional steam demand for various on-board needs. In this study this system is referred as baseline system (BL).

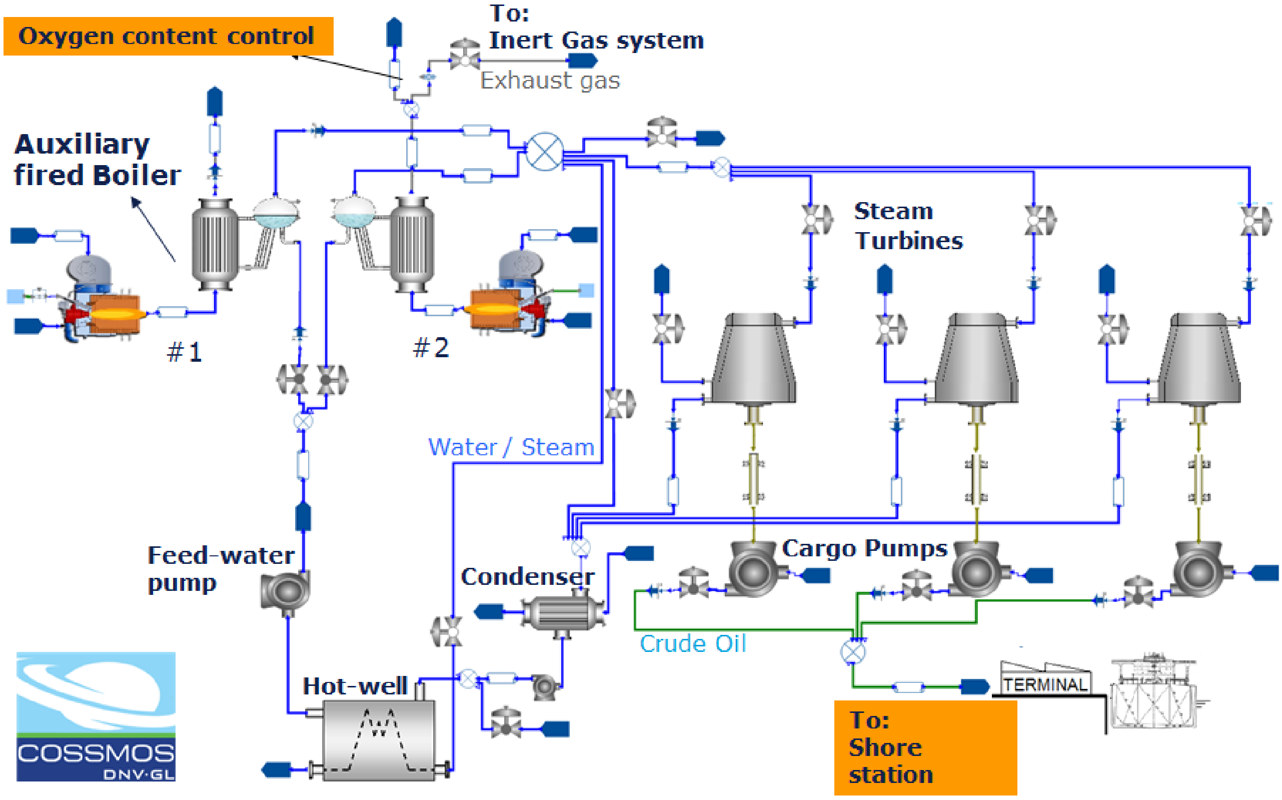


Fig. 1 COSSMOS model of typical discharge system

There is one major operational constraint that may lead to rejection of useful energy. One of the boilers is designated to feed the inert gas system, setting a limit to the exhaust gas oxygen content, which is reversely proportional to the boiler load. Thus, some combination of steam demand and steam production may lead to producing excess steam that needs to be rejected straight to the condenser. Such steam rejection takes place during emergency shut-down of the cargo pumps and during operations with only one pump at low load.

It can be observed that the BL system provides room for improvement. Therefore, three alternative systems were considered that aim at increasing the system efficiency and decreasing the fuel consumption, by utilising the rejected useful energy or a larger part of the fuel energy:

1. System A1: A micro steam turbine is installed after the steam dumping valve to utilise the rejected steam. Instead of rejecting the excess steam straight to the condenser, it is used to drive the micro steam turbine to produce electricity. This is used to cover part of the vessel's electricity demand, reducing the fuel consumption of the auxiliary engines.
2. System A2: A heat exchanger (superheater) is added after the steam drum of the boiler to utilise a larger part of the exhaust gas power. The superheated steam is then used to drive the steam-turbines in a more effective manner, reducing the required steam mass flow rate and consequently the fuel consumption. This system layout has been suggested by boilers manufacturers stating fuel savings of up to 15% depending on the vessel size and operating profile [6].
3. System A3: One steam turbine driving a pump is replaced by an electric motor drive, increasing the power conversion efficiency of the power train. The auxiliary engines fuel consumption will be increased to cover the additional electricity demands of the motor. The replacement of the drives from all three pumps would increase the electricity demand significantly, leading to the need for larger auxiliary engines. However, the size of the latter depends also on other aspects of the vessel design. Hence, such a major change would affect other phases of the design process and would limit the solution only to new-building vessels.

The three alternative designs are depicted in Fig. 2.

To manage the complexity and easily compare the performance of each system an integrated systems engineering approach is required to take into account the operation, cost, and savings of the complete system.

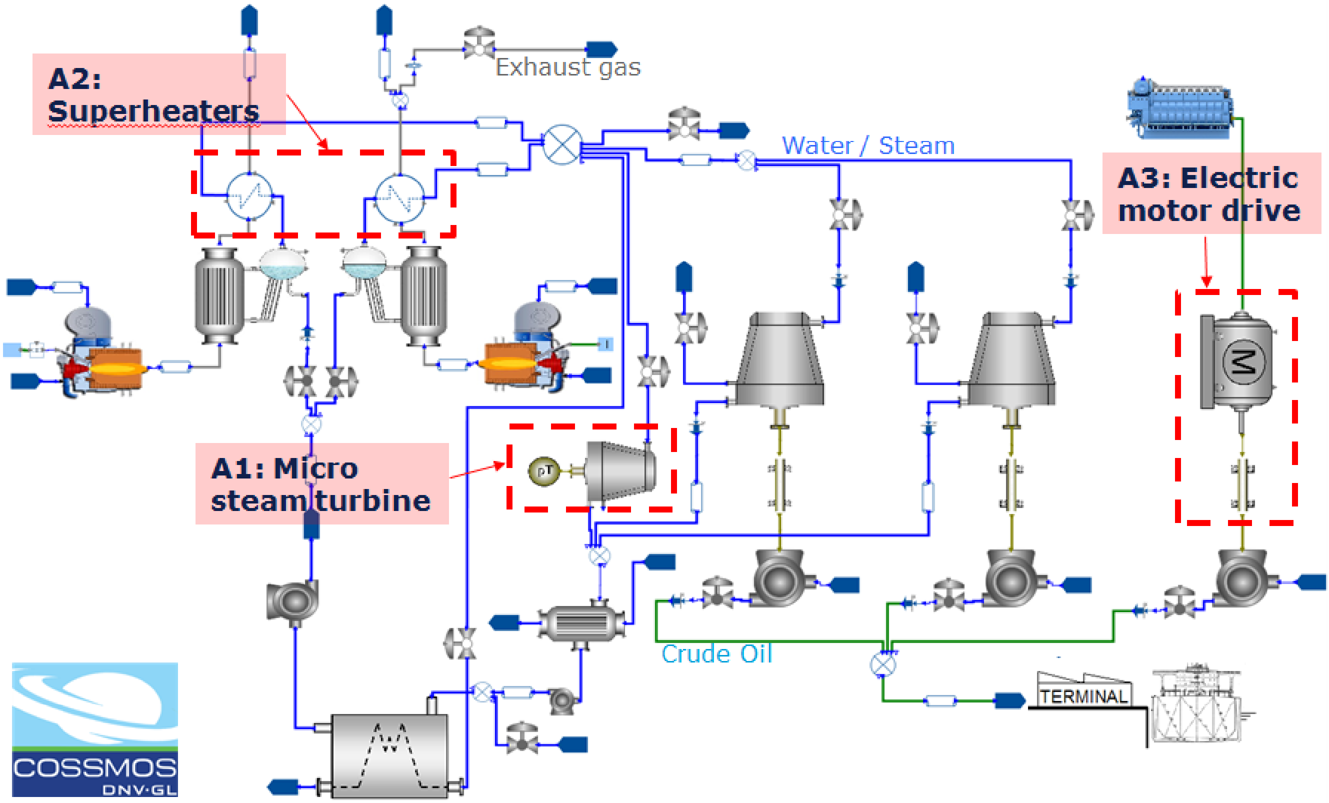


Fig. 2 COSSMOS model of alternative discharge systems

3. Mathematical model formulation

3.1. Modelling framework

Generic models of the baseline system and the alternatives have been developed in our in-house modelling framework DNV GL COSSMOS, which is an acronym for COmplex Ship Systems MOdelling and Simulation. We have developed a modular library of reconfigurable generic component models suitable for design, performance and transient operation analyses, and optimisation of integrated ship machinery systems [7-10]. This modular and reconfigurable library of component models is then used for the hierarchical synthesis of complex marine energy system flowsheets within the COSSMOS framework. The DNV GL COSSMOS framework including all the component models library have been implemented in the gPROMS process modelling environment [11].

3.2. Component models

The main system components that are used to synthesise the complete baseline system model are the boiler, the steam turbine, the centrifugal pump and the water pre-heating tank. Their mathematical formulation and the validation process are described in [5]. The boiler sub-system consists of two models: the oil-fired burner and the steam drum evaporator. The former captures the thermodynamic and flow phenomena as well as the chemical reactions of the combustion, taking into account the pressure drop in the combustor. The evaporator model is a lumped model based on the work of Åström and Bell [12]. The steam turbine model is a semi-empirical performance model that was developed using a standard methodology proposed by SNAME [13], extended and adapted to modern steam turbine generators by Dimopoulos [14]. The cargo pump model is based on manufacturers' operational maps, while the vacuum condenser models is a lumped model of shell and tube condenser type, taking into account the mass and energy conversion equations as well as metal wall heat-exchange equations.

The alternative designs introduce new component models, namely the micro steam turbine, the super-heater heat exchanger, and the electric machine. The micro steam turbine was modelled using the same model as the pump steam turbines, described previously. The superheater was modelled as a heat-exchanger, using the model described in [10, 15]. The model includes detailed heat transfer and pressure drop models, via Nusselt-type correlations and simplified momentum equations, respectively. Finally, the electric machine model is a simplified model that is based on the performance curve of the manufacturer.

3.3. System model

The component models described in the previous paragraph were used to synthesise the complete system model for the baseline system (Fig. 1) and each alternative layout (Fig. 2). Additionally to the main components, a series of auxiliary components were also used, including pipes, valves, flow junctions, etc. It should be noted that a separate model exists for each alternative system. The BL system model consists of 73 components, which include 2160 variables and 1492 differential and algebraic equations, while the alternative system models include the additional components with their respective variables and equations.

4. Case vessel and Operating profiles

4.1 Vessel and system specifications

This study presents the use of the model described in the previous section, to simulate and assess the various alternative systems for a typical Aframax oil-tanker vessel. The case vessel main dimensions are presented in Table 1. The system consists of two boilers able to produce 26 tons/h of saturated steam at a pressure of 17 bar. On the steam consumption side three pumps with nominal capacity of 2800m3/h at a total head of 130m, are driven by three steam turbines, each having a nominal power of 1210kW. The specifications of the main components are presented in

Table 2.

Table 1 Case vessel main dimensions

	Vessel
Ship type	Aframax tanker
Deadweight	105000 tons
Capacity	118000 m^3 (at 98%)
Length	180 m
Beam	42.0 m
Draught	8.4 m

Table 2 Discharge system component specifications

Steam production		*Steam consumption*	
Boiler		*Pump*	
Steam evaporation	26000 kg/hr	Capacity	2800 m^3/h
Steam pressure		Total head	130 m
- Normal working	16 kg/cm^2G	Suction head	-5 m
- Design	18 kg/cm^2G	Revolution speed	1350 (±3%) min^{-1}
- Safety	18 kg/cm^2G	Shaft horse power	1250 kW
- Hydraulic test	27 kg/cm^2G	Efficiency	85%
Fuel oil consumption	1935 kg/hr	NPSH	3.6 m
Combustion air flow rate	31160 kg/hr	*Steam Turbine*	
Heating surface	328 m^2	Inlet pressure	14.5 kg/cm^2G
Fuel type	Marine Diesel Oil	Vacuum	500 mmHg
	Heavy Fuel Oil	Power	1290 kW

4.2 Operating profiles

Information from realistic discharge operations of such vessels across one year were used to estimate an accurate annual operating profile. Three typical operations were considered, providing a low, a medium and a high discharge profile. The classification was based on the intensity of the offloading procedure, taking into account the average total discharge rate, the total discharged quantity, and the total duration of the operation.

Table 3 includes the specifications of the three typical profiles, including the annual amount of operations for each profile, while Fig. 3 present the total discharge rate during the operation for each profile.

Table 3 Typical operational profiles

Profile	*Total discharged quantity, t*	*Average offloading capacity, m^3/h*	*Duration of the operation, h*	**Annual operations, -**	Percentage
Low	30,000	800	37	**8**	25%
Medium	84,000	3500	24	**16**	50%
High	100,000	6200	16	**8**	25%

Twenty five operational variables from the actual operation were used as input to the model for each operational point of each profile, including operating pressures, mass flow rates, pump characteristics, etc. It should be noted that during the actual operations the decisions made by the crew were not always optimal leading to higher fuel consumption [5]. In this study, the variables that demonstrated room for improvement were changed so as to perform optimal operation. Hence, the savings that will be identified by the model refer to optimal operation of the system.

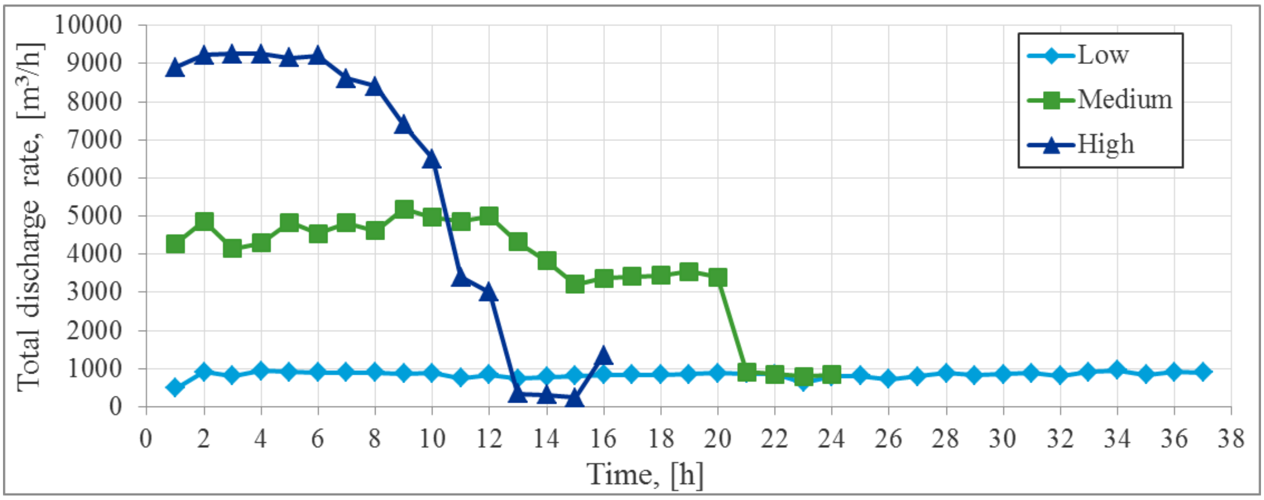


Fig. 3 Total discharge rate across time for each typical profile considered

4.3 Economic data

The cost estimates of the additional components were based on cost figures from [16] and include the installation costs, as shown in Table 4. It should be noted that the component and installation costs may vary significantly between applying the system design as a retrofit solution and as a new-building (NB) one. While the micro steam turbine cost remains constant for both options, the cost of the superheater is decreased significantly and the cost of the electric motor is negligible (or even negative) due to the removal of one steam turbine. The sizing of the components was based on the system specifications and limits, and on the expected rejected steam for the case of the micro steam turbine, as described in the following section.

Table 4 Economic data

	Retrofit cost [$]	*New-building (NB) cost [$]*
Micro steam turbine	150,000	150,000
Superheaters	50,000	40,000
Electric motor drive	70,000	0

There are two types of fuel that are used typically in those systems, namely Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) assumed at 300$/ton and 570$/ton, respectively [17]. Since 1st January 2015 vessels operating within Emission Control Areas (ECAs) are obliged to use low-sulphur fuel, i.e. MDO, according to MARPOL Annex VI [18]. Currently, the North American coast, the North sea and the Baltic sea are considered ECAs, while the Mediterranean sea and the Japanese coasts are proposed ECA. In addition, in 2020 the low-sulphur limit will be effective even outside of ECAs at a global level. We assume that the case vessel operates exclusively within European and Mediterranean portsl thus only MDO was considered as fuel. It should be noted that the price of fuel may change significantly over time. At the time of this study the fuel price was considered a decade-low after being over 1000$/ton for the last decade. Therefore, it is of major importance for the techno-economic appraisal to perform a sensitivity analysis with respect to the fuel price.

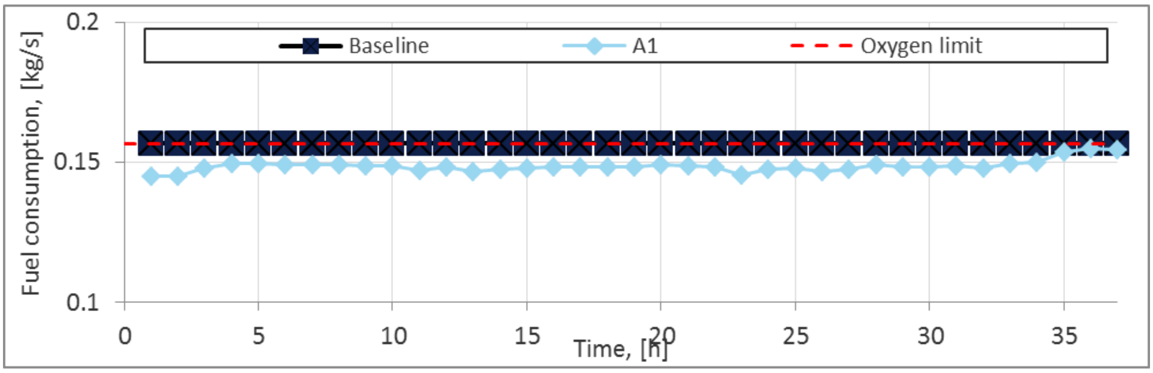
Finally, the market interest rate for the calculation of the Net Present Value (NPV) of the investment was considered at 8%.

5. Results and comparison

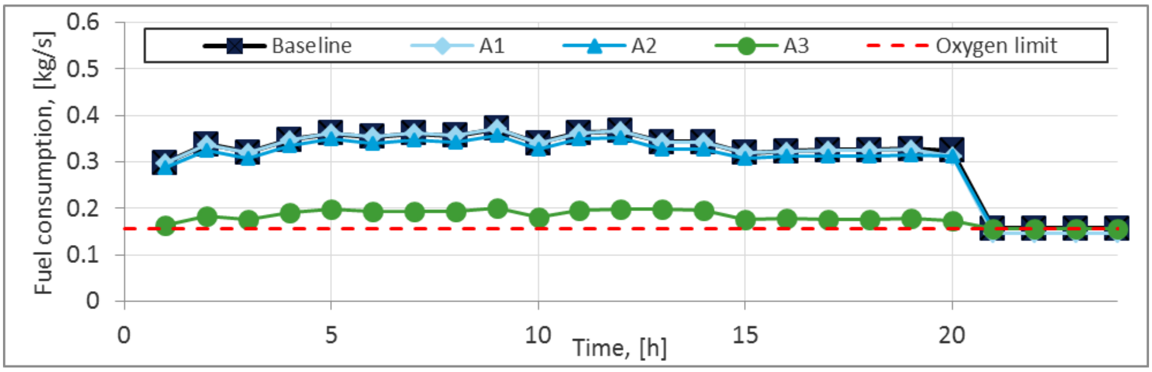
The three operating profiles described in the previous section were used as input in the model to perform the simulations. For each one of the four systems, three simulations were performed, one for each profile. First, the simulation of the baseline system was executed to assess what is the typical amount of the rejected steam so as to size the micro steam turbine, as described in the following sub-section. The other two additional components were sized based on the system performance limits and constraints.

The instantaneous fuel consumption of each system for each profile is presented in Fig. 4. In the low profile only the microturbine option provides significant savings as the pumping needs and consequently the steam demand are very low. On the other hand, in the medium and high profiles, large savings of 10-20% are identified for the electric motor solution and moderate savings of 4-6% for the superheater option.

The following sub-sections describe the sizing and results of each system alternative and the last sub-section presents the techno-economical appraisal of the alternative options based on the annual savings.



(a)



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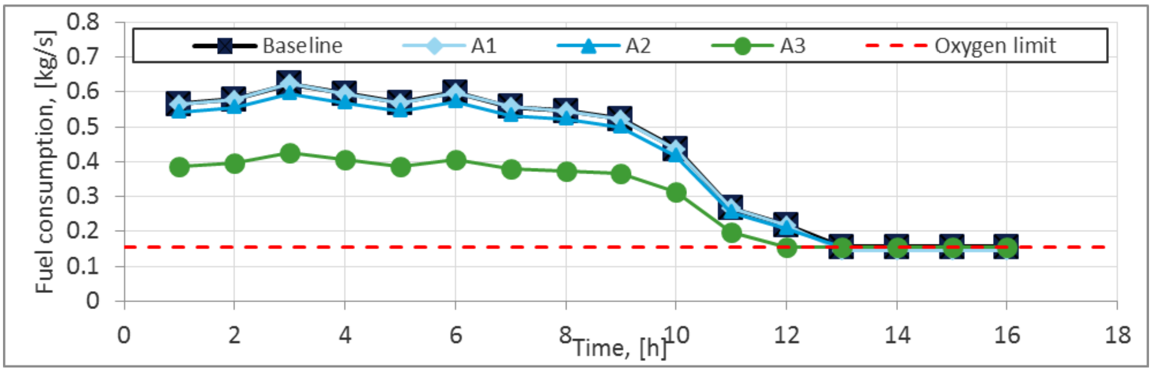

(c)

Fig. 4 Fuel consumption of each system across the operation for profile: (a) low, (b) medium, and (c) high

5.1 System A1 – micro steam turbine

The micro steam turbine was sized based on the typical steam rejection. As described in the previous chapters, the rejection takes place during emergency situations and when the steam demand is very low forcing the boiler to operate at the low limit load to produce exhaust gasses with oxygen content within the limit (4.7%). In the medium and high profiles steam dumping takes place only during the last four hours where the operation is almost finished and the total capacity is very low (Fig. 4). However, in the low profile steam rejection takes place during the whole discharge operation. Therefore, the size of the micro steam turbine was selected as the maximum of the steam that is rejected continuously during the low profile, as presented in Table 5 .

Table 5 Micro steam turbine specifications

Variable	Value
Shaft horse power	190 kW
Nominal steam flow	0.32 kg/s
Capital cost	150,000 USD
Capital cost (NB)	150,000 USD

The fuel consumption was integrated over the complete operation to estimate the total required fuel for each profile as presented in

Table 6. The fact that steam is rejected constantly during the operation in the low profile leads to fuel savings of 1.1 tons per discharge. On the other hand, in the medium and high profile the savings are marginal at 0.2 tons per discharge. It should be noted that optimal operations were assumed as input to the simulations. In real conditions the steam rejection is significantly larger even when it is not actually required.

Table 6 Fuel consumption for A1 system (micro steam turbine) for each profile

Profile	*Baseline [t]*	*A1 [t]*	*Savings [t]*	*Savings [%]*
Low	20.9	19.8	1.1	5.1%
Medium	26.7	26.6	0.2	0.6%
High	24.2	24.0	0.2	0.7%

5.2 System A2 – superheater

A separate superheater was considered for each boiler. They were equally sized based on the maximum temperature of the inlet steam in the steam turbines. The upper limit set by the manufacturer is 543 K. The heat exchange surface was selected so as to produce superheated steam at this temperature during the nominal load operation of the boiler, namely 26t/h. In addition, the temperature of the exhaust gas after the superheater should be above 450 K to avoid condensation which leads to corrosion of the funnel. The main specifications are presented in Table 7.

Table 7 Micro steam turbine specifications

Variable	Value
Heat exchange surface	120 m^2
Max. outlet steam temperature	543 K
Capital cost	50,000 USD
Capital cost (NB)	40,000 USD

The savings for each profile are shown in Table 8. In the low profile, the superheaters have no effect as the boiler is already operating on its low limit due to the oxygen content constraint. In the medium and high profiles moderate savings were identified, namely 3.5% and 4.1%, respectively.

Table 8 Fuel consumption for A2 system (superheater) for each profile

Profile	*Baseline [t]*	*A2 [t]*	*Savings [t]*	*Savings [%]*
Low	20.9	20.9	0.0	0.0%
Medium	26.7	25.8	0.9	3.5%
High	24.2	23.2	1.0	4.1%

5.3 System A3 – electric motor drive

The electric motor drive was sized based on the steam turbine that it replaces. A variable frequency drive was considered so as to maintain the ability of the crew to decide the speed of the pump. The main specifications are given in Table 9. It should be noted that in operations that only one pump is required, a steam-driven pump has to be selected, since the boiler will operate to feed the inert gas system and cover other steam demands of the vessel. The capital cost for retrofit is estimated at 70k USD. However, in the case of the NB solution the capital cost will not include the cost of one steam turbine. Therefore, a zero capital cost is considered for system A3 as a NB solution.

Table 9 Electic motor drive specifications

Variable	Value
Rated power	1290 kW
Rated efficiency	97 %
Capital cost	70,000 USD
Capital cost (NB)	0 USD

The savings were estimated taking into consideration the additional fuel that should be used by the auxiliary engines to cover the motor drive electric power demand. The total savings per profile are presented in Table 10. In the low profile, there is no effect on the fuel consumption as the boiler is already at its low load of operation. On the other hand, in the medium and high profile the predicted fuel savings are significant. In the former 6.8 tons may be saved per discharge operation, while 4.2 tons in the latter, which corresponds to 25.6% and 17.5% respectively.

Table 10 Fuel consumption for A3 system (electric motor drive) for each profile

Profile	*Baseline [t]*	*A3 [t]*	*Savings [t]*	*Savings [%]*
Low	20.9	20.9	0.0	0.0%
Medium	26.7	19.9	6.8	25.6%
High	24.2	19.9	4.2	17.5%

5.4 Techno-economic appraisal

The predicted savings described in the previous sub-sections were used to perform the techno-economic analysis and comparison of the proposed systems. The total required fuel for each profile is given per system in Table 11 and shown in Fig. 5. It is observed that the electric motor drive is the most promising solution as it demonstrates the highest savings in the medium and high profile.

Table 11- Fuel consumption [ton] for each design and operating profile

Profile	*Baseline [t]*	*A1 [t]*	*A2 [t]*	*A3 [t]*
Low	24.2	23.1	23.2	19.9
Medium	26.7	26.6	25.8	19.9
High	20.9	19.8	20.9	20.9

The annual operating profile (

Table 3) was used to estimate the annual savings for each alternative system. These were used along with the capital cost to estimate the Net Present Value (NPV) and Discounted Payback Period (DPB) of each system, including the NB solution. A market interest rate of 8% and a period of investment of 10 years were assumed. The assumed case vessel operates between European and Mediterranean ports. As described in sub-section 4.3, for this study it was assumed that the vessel operates only on MDO. The techno-economic results for the case vessel are given in Table 12.

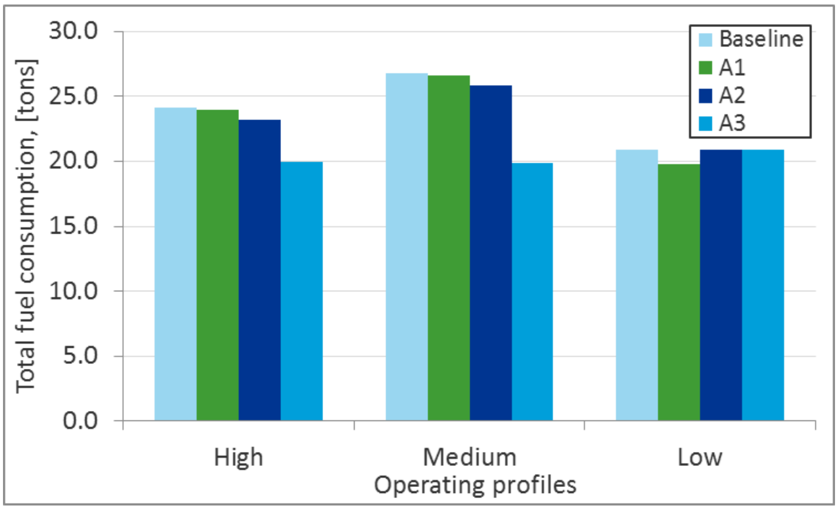

Fig. 5 Total fuel consumption for each operating profile per system layout

Table 12 Techno-economical data for each alternative system

	A1 – micro steam turbine	A2 - Superheaters	A3 – Electric motor drive
Annual fuel savings, tons	12.6	22.8	143.2
Annual cost savings, USD	6,785	12,310	77,340
Capital cost, USD	150,000	50,000	70,000
NPV, USD	-104,470	32,615	448,950
Payback period, years	N/A	5.1	1.0
Capital cost (NB), USD	-	40,000	0
NPV (NB), USD	-	42,615	518,950.1
Payback period (NB), years	-	3.9	0

It is observed that the A3 system demonstrated the highest annual cost savings at 77,340 USD, followed by the A2 system and A1 system at 12,300 USD and 6,785 USD, respectively. In addition, it is observed that the capital cost of the systems is not proportional to the savings ranging from 200k USD, to 50k USD and 70k USD for the A1, A2, and A3 systems, respectively. Therefore, the NPV of the A3 system is significantly higher than the rest at 449 kUSD. The A2 system demonstrates an NPV of 33 kUSD and the A1 a negative one, which means that for an investment duration of 10 years this system is not a feasible investment. Finally, the payback period of the A3 system is approx. one year making it a promising investment and the best among the three designs. The A2 system payback period is at 5.1 years, and the A1 over 25 years, which exceeds the life of the vessel. For the NB solution the A1 system demonstrates the same results, as the capital cost is the same as in the retrofit solution. The NPV for system 2 is increased to 43 kUSD, while the payback period is decreased to 3.9 years. Finally, since the cost of system A3 compared to the original design is 0 USD, the payback period is zero and the NPV is increased to 519 kUSD, making system A3 an even more attractive alternative to consider.

The estimated payback periods include a level of uncertainty with regards to the fuel price and the capital cost. The former may vary significantly over time, e.g. the price of MDO decreased from 1100 USD/ton on September 2014 to 570 USD/ton on January 2015. The latter may vary depending on the manufacturer, economic conditions, and the amount of orders for similar vessels. Therefore, a sensitivity analysis for those two variables was performed for each system. The fuel price ranges from 300 USD/ton to 1100 USD/ton, while the capital cost ranges from 50% to 150% of the initial estimation.

For all three systems the lowest payback period is at a fuel price of 1100 USD/ton and 50% capital cost, while the highest for 300 USD/ton and 150%. The DPB of System A1 varies from 5.9 years to not economically feasible, while of the system A2 varies from 1.8 to 25.0 years, as shown in Fig. 6 and Fig. 7, respectively. The A3 system demonstrates a promising variation as it ranges from 0.2 to 2.8 years. Therefore, it should be noted that system A3 is the most favourable investment demonstrating low DPB even during negative economic conditions.

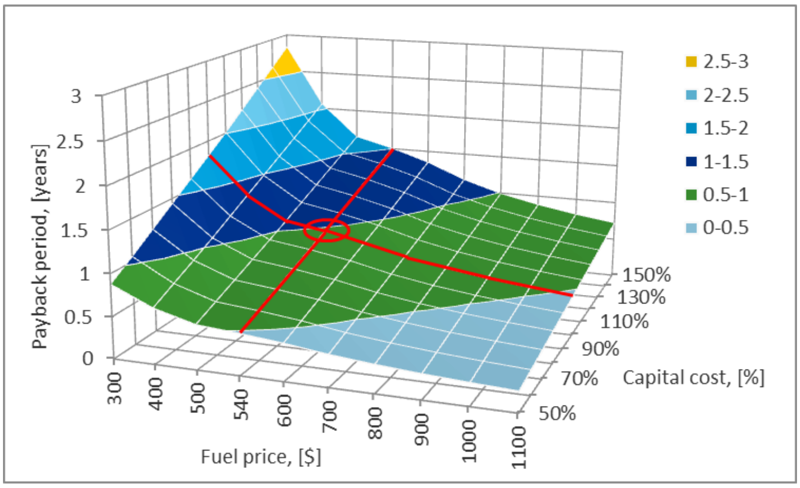

Fig. 6 Sensitivity analysis of fuel price and capital cost for system A1 (micro steam turbine)

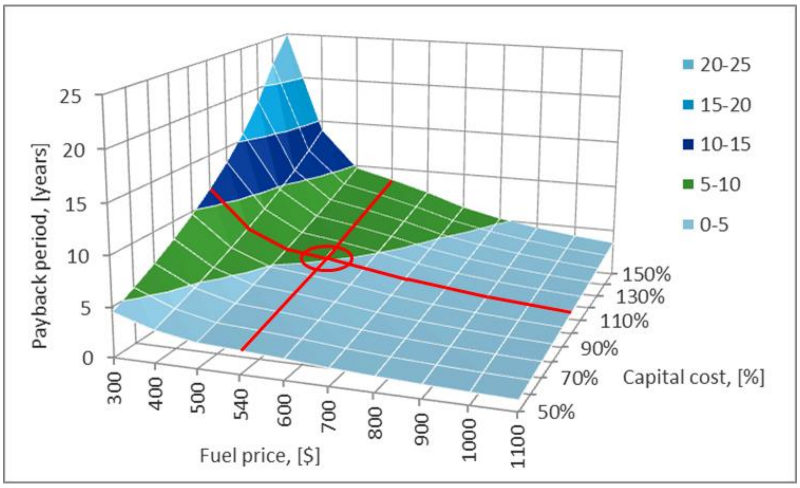

Fig. 7 Sensitivity analysis of fuel price and capital cost for system A2 (superheater)

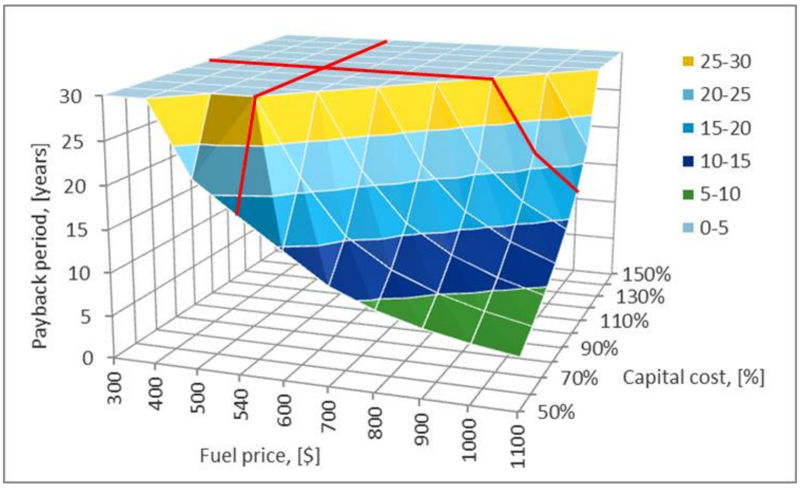

Fig. 8 Sensitivity analysis of fuel price and capital cost for system A3 (electric pump)

6. Conclusions

In this paper, we have presented the techno-economic analysis and comparison of alternative system configurations for the cargo-oil discharge system of oil tankers via mathematical modelling

simulation techniques. The alternative options include the addition of a micro steam turbine to utilise the excess steam that is rejected from the system, the superheating of the steam that drive the steam turbines, and the replacement of one steam turbine with an electic motor drive. A model was developed for each system in our modelling framework COSSMOS. Data from realistic operations of an Aframax tanker were used to identify three typical profiles and estimate the annual operating profile. Data from the measurements were used as input to the COSSMOS model.
The results indicate that there is good potential improvement by replacing the steam turbine with an electric motor drive. With annual savings of 77k USD and a capital cost of 70k it demonstrates a payback period of approx. one year. On the other hand, the other two solutions provide significantly less fuel savings, and thus the payback periods are at 5 and over 25 years for the superheaters and micro steam turbine respectively. The systems A2 and A3 demonstrate even better techno-economic results for the case of NB, namely 3.9 years and instant payback respectively.
Finally, a sensitivity analysis was carried out with respect to the fuel price and the capital cost, indicating that the proposed replacement of the steam turbine is a feasible and promising solution even at economic conditions with very low fuel prices and high capital cost.

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